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Swiss pumped hydro storage potential for Germany's electricity system under high penetration of intermittent renewable energy

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Abstract In order to cut greenhouse-gas emissions and increase energy security, the European Commission stimulates the deployment of intermittent renewable energy sources (IRES) towards 2050. In an electricity system with high shares of IRES implemented in the network, energy balancing like storage is needed to secure grid stability and smooth demand satisfaction. Pumped hydro storage (PHS) is at this moment the best option for large scale storage. Switzerland has strong ambitions to further develop their PHS sector and become the battery of Europe. In this research, the potential of the Swiss PSH plants is explored, whilst taking inflow into the upper reservoirs of the PHS plants into consideration. To simulate electricity imbalance, Germany is used as a case study. Germany already has a high penetration of IRES and has plans to increase installed IRES capacity. By using an energy planning model (PowerPlan), three future scenarios of the German electricity system were designed, each with a different set of IRES installed (*solar*, *mixed* and *wind*). Results show that the Swiss battery ambition offers most benefits to a wind-oriented scenario, reducing both shortages as well as surpluses. Water inflow in Swiss PHS-reservoirs is of minor importance when looking at security of supply, although it was shown that the *solar*-scenario profits more from inflow in terms of system stability. However, a potential conflict was observed in the *solar*-scenario between the need for electricity storage and the storage of natural inflow, resulting in more surpluses in the system when inflow was taken into account.

Keywords Pumped hydro storage (PHS), Local hydrology, Germany, Switzerland, Intermittent renewable energy sources (IRES), Scenarios

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1 Introduction

In the light of raised concerns on the effects of climate change, the European Commission developed several strategies to reduce its greenhouse gas emissions towards 2050 [1]. The aim of the targets set is to cut emissions, improve energy efficiency and to invest in the deployment of renewable energy sources. However, the highly variable nature of renewable energy sources imposes a problem for the continuity of supply of electricity. This will be even more pronounced when high shares of intermittent renewable energy sources (IRES), like photovoltaics and wind power, are integrated into the electricity network. In order to secure grid stability and smooth demand satisfaction in a system with a high penetration of IRES, storage of energy is often proposed as solution [2, 3]. Multiple storage solutions exist on the market, but many of those technologies are expensive, making pumped hydro storage (PHS) the only profitable option considered [4]. Currently, around 99% of storage capacity worldwide is delivered by PHS-systems [4].

PHS plants have the ability to store off-peak electricity by pumping water from the lower reservoir into the upper reservoir and release it during peak-demand periods to generate electricity. They can react within seconds to the variations in production and consumption, thereby ensuring sufficient energy supply and contributing significantly to the stability of the network [5]. Pumping and generating generally follows a diurnal cycle, but weekly or even seasonal storage of water is possible with larger PHS-plants [6]. Essential to any project is the elevational difference between the two reservoirs, which limits the number of potential sites for PHS systems to mountainous countries [6]. Two types of PHS plants can be distinguished: pure PHS-plants, which are often small-scale systems designed to balance short-time variation and large-scale PHS-plants which are part of a hydrological system. The latter are not always closed-loop systems; some plants receive a considerable amount of natural inflow into their reservoirs on an annual basis, while others are hydraulically coupled within a network of multiple hydropower plants [7]. Furthermore, residual flows towards lower lying areas need to be managed for ecosystem conservation and agricultural services [8].

Within Europe, Swiss electricity companies state that the countries' network of PHS-plants within the Alps can serve as the "battery of Europe" [3, 9]. In addition to that, the country seeks a better connection with the EU-market to increase the profitability of current and future PHS-projects [10, 11]. Currently, fourteen PHS plants are running in Switzerland with a combined installed capacity of 1380 MW [12] and an estimated potential storage of 369 GWh of energy [13]. Furthermore, three projects are under construction, increasing Swiss pumped-storage capacity to 3760 MW in the coming decade [12]. However, these three projects are not closed-loop systems and the amount of water flowing into these Swiss reservoirs is highly seasonal dependent, since these installations rely both on rainfall and on glaciers situated on higher altitudes that feed the reservoir during the melting season [14].

The main reason for the expansion of the Swiss PHS-sector is the planned divestment from nuclear energy, aligned with an increase in the use of renewable energies such as wind power and photovoltaics [15]. The responsibility to secure reliability of supply in a network with high shares of IRES is a change in the business case for the Swiss PHS-sector and the implications of this shift from peak-load operator to "guarantor in the energy turnaround" so far remain unclear [3].

In general, studies that model the relationship between IRES and PHS-plants seek to maximize financial profits of the combined system [16–22]. Other work encompasses system planning and reliability [23], effects of battery implementation on total system emissions [20], or investigates the optimal size of a PHS-plant given large shares of IRES penetration [24]. We found no research that investigates the Swiss storage potential for an electricity system which contains high shares of IRES in the network in relation to the local hydrological dynamics. This is therefore the central point of investigation within this paper.

Within this research, the aim of Switzerland to become the battery for Europe is tested by using the German electricity system as an example case. Currently, Germany has around 7.6 GW of PHS installed within its own borders. In their pursuit to become less dependent on nuclear energy and imports and set targets to reduce carbon dioxide emissions (which means a reduction in lignite power plants), Germany plans to invest (a lot) in the deployment of IRES in the coming decades. The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) has planned to produce 80% of the 2050 electricity demand from renewable energy sources. It is estimated that of the final German electricity demand 52% comes from wind (38% offshore and 14% onshore) and 15% from Photovoltaics towards 2050 [25].

However, the German potential to expand the installed capacity of its PHS sector within its own borders is thought to be limited due to a lack of site availability [6, 25], although some emphasize that the German "Energiewende" created a new momentum for the hydropower sector [6, 26]. Still, Germany seeks a connection with other European countries that potentially could store electricity surplus in their PHS plants [27, 28]. Since Switzerland neighbors Germany and contacts already exist on potential cross-border trade, Germany is considered a valid example case [28].

Thus, the central aim of this research is to assess the important parameters and dynamics in relation to Switzerland's PHS-sector, while taking the intermittency of the IRES into account as well as the variations in water availability. In order to do so, it is chosen to focus on the battery potential of Switzerland for the German electricity system.

2 Methods

In order to investigate the functioning of the Swiss PHS-sector (with its specific hydrology) within a system containing high shares of IRES, the German electricity system was modelled within the model PowerPlan. PowerPlan is an electricity planning model which was developed the mid- eighties and had been improved continuously [29, 30], see Section 2.1.

Within this research, three main-scenarios were developed, representing different potential future states of the system. Next, the Swiss PHS-sector was added to this model. Scenario comparison allowed to investigate the effect of the different surplus- and shortage-patterns of the German electricity system on the potential role for the Swiss PHS-sector. Furthermore, the designed system was used to study the effects of taking local hydrology into account.

2.1 The PowerPlan model

PowerPlan is a deterministic bottom-up tool in which each plant can be defined separately. It simulates electricity demand and production from a centralized planning perspective, which allows the exploration of 'what if' scenarios. The model provides a flexible and dynamic modelling environment for mid- to long-term electricity supply planning and scenario studies, which makes it highly suitable to do the calculations for this research. PowerPlan simulates investment decisions in capacity expansion and produces results including generation costs, system reliability, fuel use and environmental emissions. The core of the PowerPlan model is the production simulation module in which the demand has to be met by the supply using the merit order approach. Calculations are performed on an hourly basis.

The model offers two merit-order approaches: either based on marginal costs, or the merit-order can be assigned by the user based on user assumptions or preferences. Because we want to explore potential consequences of differential implementation of the PHS plants to the electricity system, this last approach is used in this study (see Section 2.3.1). The defined power plants are placed in order of the merit (see Table 2 and Appendix A). Within each defined type of plant, the newest plant is placed higher in the merit order. The last option is by changing the plants' typical label (base, middle or peak load). For example, if a new highly efficient, cleaner combined cycle (CC)-plant should be placed higher in the merit order then an old coal-fired power station, the CC-plants' label could become "Base Load" while the coal-fired power plants' label becomes "Middle Load". In this case the CC-plant is placed higher in the merit order. For scheduled maintenance and unplanned outage, the existing capacities are de-rated for operation & maintenance by a fixed fraction throughout the year (see Appendix A). The model was previously used in the contexts of developed and developing countries [29–32].

The representation of system reliability is parameterized by the loss of load probability (LOLP) and energy shortages [33]. The LOLP is a measure for the number of days per year in which the demand is higher than the production, see (1). The shortages are the amount of energy (GWh) that could not be delivered, see (2). Besides this, PowerPlan gives also the surplus of electricity generated. This surplus occurs when intermittent sources like wind and photovoltaics and so-called "must-run" capacity like nuclear power stations produce more electricity than the final demand.

$$LOLP = \sum_{t=1}^{8760} D_t > P_t \tag{1}$$

$$Shortage = \sum_{t=1}^{8760} D_t - P_t \quad \forall D_t < P_t \tag{2}$$

where D is the demand (MW) per hour and P is the production per hour.

In an annual cycle, the demand is determined by the peak load and the normalized hourly demand pattern. To simulate intermittent energy sources (wind and solar PV) multiple normalized hourly patterns can be used. The Swiss PHS-plants can receive an inflow into their upper reservoir, which is based on the Pardé-coefficients as explained in Section 2.3. The monthly influxes are equally divided over the hours within a month. The surpluses are allocated to the plants based on the relative storage potential of the individual plants: within each hour, the natural inflow is added to the reservoir first, and subsequently available surpluses will be stored in the upper reservoirs. The PSH plants with the lowest upper reservoir level compared to its maximum, receives most surpluses.

2.2 Modelling the German electricity system

Within the PowerPlan model, the electricity system of Germany was assumed to be centralized and isolated from other European countries. This means that the interconnection with the Scandinavian countries, as well as the electricity dump during summer periods (caused by high IRES production) to neighboring countries are left out of the simulation. This choice is based on the aim to study the effect of Swiss PHS-plant on the German system explicitly. When other imports and exports would be taken into account, this would affect the researched system. In that case the effect of adding the Swiss PHS-plants would be mixed up with other imports/exports.

The transmission and distribution system was assumed to deliver power with an overall efficiency loss of 5%. The hourly demand pattern from 2012 was obtained from the European Network for Transmission System Operators for Electricity [34] and is depicted in Fig. 1a. Table 2 renders the installed capacity per technology in 2012 [34].

The PowerPlan model calculates the IRES-power generation via weather dependent production patterns. The simulation included 5 different intermittent-RES generation sites; site selection was based on the German provinces with the highest and lowest wind and solar installed capacity, as well as a site for offshore wind measurements.

Two hourly onshore wind-speed measurements were selected from weather stations [35]. The hourly wind-speed for offshore wind was obtained from the FINO 1 monitoring station in the North Sea [36]. Wind-speed data were corrected for the difference between the measured height and the height of the turbine rotor and roughness of the area around the wind turbines according Wieringa and Rijkoort [37]. The resulting wind-speed is converted into power production using the power curve of a 2 MW turbine. The solar hourly production patterns were determined from a global solar radiation data obtained from the SODA website [38]. The resulting production patterns based upon those normalized IRES patterns were reported to have similar yields when compared to historical production data [39], as shown in Table 1.

The comparison of Table 1 shows that most of the intermittent behavior of wind and *solar* PV is captured with the chosen patterns. Those patterns are used in the scenario development of the increase of IRES capacity towards 2050. Figure 1 provides two examples of the used *wind* and *solar* production patterns; one onshore wind pattern Fig. 1b and a solar pattern Fig. 1c. The solar production pattern exhibits a high degree of seasonality; wind power is less periodic.

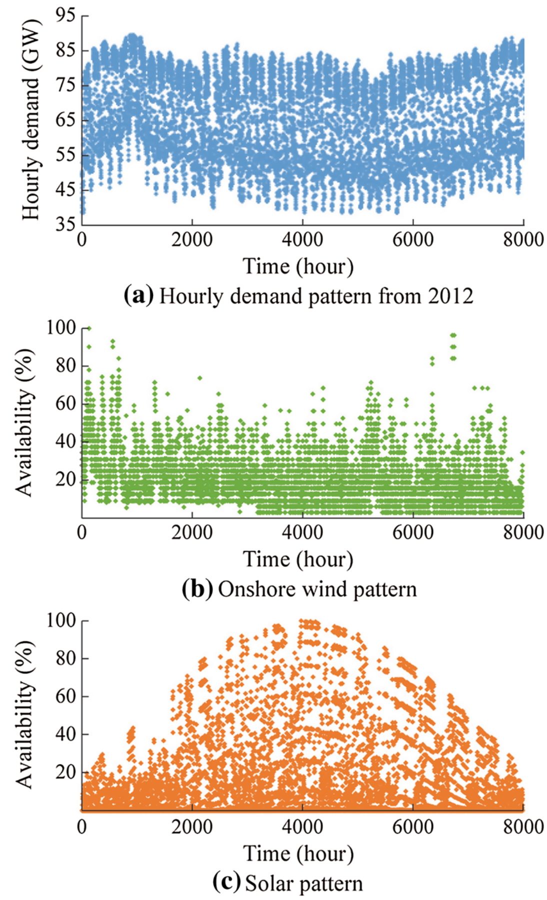


Fig. 1 Modeling the German electricity system: yearly patterns in which each dot represents one of the 8760 hours. **a** gives the hourly demand pattern for 2012. **b** and **c** represent the hourly availability of IRES normalized to maximum production. Two patterns are shown; **b** renders wind availability of northeast Germany, and (**c**) depicts solar-PV availability of southeast Germany

Table 1 Electricity production of photovoltaics and wind as a share of the final electricity production in 2012

Technology	PowerPlan 2012	ENTSO-E 2012
Solar	4.72 %	5.12 %
Wind	8.85 %	8.52 %

2.2.1 *Scenario development towards 2050*

According to the objectives of the BMUB, German electricity demand should be reduced with 25% by 2050 [40]. Nevertheless, electricity demand could also increase due to electrification of both the heat and the transport sector [41, 42], for example due to an increase in the adoption of electric vehicles [41]. Schlesinger et al. differentiate between target scenarios (around 460 TWh by 2050) and trend-based scenarios (560 TWh) for future German electricity demand [43]. Larger increase is predicted as well, up to 700 TWh of final electricity demand [44]. Here, the final electricity demand of Germany is assumed to slightly increase toward 594 TWh by 2050, relating to a total growth of 5% compared to the 2012 demand.

Capacity development towards the year 2050 of the different renewable energy as well as the conventional power systems was modeled according to three main criteria. First, the renewable energy capacity development was devised in relation to the BMU objectives; 80% of renewable electricity generation by 2050 [25]. Second, the maximum potential for biomass thermo-chemical conversion of 1100 PJ/yr was taken from Thrän and Kaltschmitt [45], and is assumed to be entirely available for power production. Third, the rest of the required renewable energy capacity to meet the BMU objective was achieved by expanding wind power and solar-PV. The used ratio between wind-offshore, wind-onshore and PV is in line with the ratio used in a BMWi study [28]. The remaining 20% of the generation capacity was covered by gas and coal generators.

Three scenarios were developed that describe comparable future states of the German electricity system, each with a different relative role for the IRES. An overview of the scenarios can be found in Table 2.

In general, a power system is considered trustworthy when it has a LOLP of less than ½ days/year. In this study, the LOLP is chosen to be the relatively high value of 7 days/year. This value is chosen arbitrary: not too high but high enough to show the difference which will occur in the scenarios. LOLP values in all scenarios should be higher than 0 to be able to measure the effect of adding the Swiss plants to the system. The main interests within this study lies in the relative differences across sub-scenarios.

The first scenario assumes high investments into photovoltaics ("*solar*"), and was developed based on the three criteria as described above. The *mix*-scenario has less photovoltaics installed and more wind, while the *wind*-scenario makes the exact opposite assumption to the *solar*-scenario: the installed capacity of solar energy is kept similar to current levels (around 40 MW_{peak} at the end of 2015 [46]), whilst the shift from solar PV to wind is done in such a way that the overall system stability is comparable to that of the *solar*-scenario (LOLP = 7 days/year). The installed capacity for the remaining plants is kept equal across the three scenarios.

Table 2 gives an overview of the total installed capacities per technology for each of the developed IRES-scenarios.

Note that while the three sub-scenarios of the German electricity system have an equal LOLP, the scenario do show a different Reserve Factor (*solar*: 4.1, *mix*: 3.7 and *wind* 3.4). This means that with the same demand, less installed capacity is necessary to create an equally stable system for the *wind*-scenario compared to the *solar*-scenario (see Table 3 for total installed capacities). This can be explained by the differences in the capacity factors of the two renewables: for wind farms, load factors range between 20% and 28% for onshore wind turbines, and 35% for offshore wind farms, while the load factors for solar PV vary from 13% to 14%. Final electricity demand is equal for all scenarios (594 TWh).

Table 2 Total installed capacity (MWe) per technology in 2012 and for the three developed IRES-scenarios. The order in this table equals the merit order

Technology	2012	2050		
		solar	*mix*	*wind*
Nuclear*	12131	–	–	–
Solar	33014	122301	76966	41610
Wind onshore	31837	119056	122356	129058
Wind offshore	508	56369	61169	65369
MSW	4223	3000	3000	3000
R-Hydro	5005	3911	3911	3911
S-Hydro		1393	1393	1393
Coal	46595	6000	6000	6000
Biomass	5922	12783	12783	12783
Pump-Hydro	8882	15166	15166	15166
CC	22342	43760	43760	43760
Gas turbine	9900	–	–	–
Total	180359	383739	346504	322050

Note: * In Appendix A, plant characteristics are given

2.3 The Swiss PHS-plants

Besides the fourteen pumped storage plants that are already running in Switzerland, three projects are under construction, increasing Swiss PHS capacity to 3670 MW in the coming decade [12]. These three plants (Limmern, Nant de Drance and Veytaux) are supposed to serve at least partly as a battery for Europe [3, 10]. In practice, the whole system of all PHS-plants in Switzerland will be part of this battery plan, but for the sake of the simulation only these three plant are considered to be fully available for the European battery function and all others not. Furthermore, water overflow from the upper reservoir as well as potential flows towards lower lying areas are assumed to leave the system unused.

Table 3 summarizes the main characteristics of the three PHS projects at the end of their commissioning phase. The projects Limmern and Nant de Drance both entail the construction of new underground infrastructure to allocate the pumps and an expansion of the upper reservoir towards 25 million m^3 [48, 49]. At the Limmern project, the lower reservoir will remain connected to the already existing Linth-Limmern scheme, which is left out of the analysis. The Veytaux PHS plant will be equipped with extra pumps and turbines, doubling current installed capacity to 480 MW [50].

Both the upper as well as the lower reservoir of the three plants experience a water influx from rain and meltwater. Since storage potential depends on the capacity of the upper reservoir, this research focuses on the inflow into this reservoir.

Table 3 Plant specific data of Limmern, Nant de Drance and Veytaux. Data derived from [47]

Parameter	Limmern	Nant de Drance	Veytaux
Turbine capacity (MW)	1000	900	480
Pumping capacity (MW)	1000	900	480
Hydraulic head (m)	630	425	800
Upper reservoir size (mil. m^3)	25	25	52
Lower reservoir size (mil. m^3)	92	227	89000
Storage capacity (GWh)	35	23.5	92.1
Inflow (mil. m^3)	5.4	8.7	100.2
Inflow (GWh)	7.5	8.2	177.6

Note: Data derived from [47]

The Hydrological Atlas of Switzerland gives the long-term averages of seasonal variation of runoff for different catchments [51]. The different runoff regimes can be described by the use of the dimensionless Pardé- coefficients, which are defined as the quotient of monthly over annual runoff [51].

Figure 2 shows the inflow patterns which describe the quantity of water running into the three PHS-systems. Patterns are derived by combining data from different tables of the Hydrological Atlas [51]. The annual average flow MQ (m^3/sec) was based on catchment area size in square kilometers Fn (km^2) (Table 5.2) and averaged yearly runoff estimates q (l/km^2) from Table 5.4 of the Hydrological Atlas, assigned to the plants through the corresponding identification number of each Swiss lake. Then, the average annual flow MQ was expressed in million cubic meters of water per year. The division over the months of this annual inflow was calculated using the Pardé Coefficients from Table 5.2 of the Hydrological Atlas [51]. Within the PowerPlan model, the data on annual inflow (million m^3) into the systems is expressed into a total amount of energy (in GWh/year, see Table 2) and monthly division again based on the Pardé coefficients.

2.3.1 System-sensitivity: merit-order issues

Within the PowerPlan model, the merit-order of the different techniques can be assigned by the user. When a PHS-plant operates earlier in the merit order, it might replace conventional capacity during some hours in the year, lowering overall emissions produced. Also, a plant in middle load will operate more often, emptying its upper reservoir and consequently can offer more storage capacity to the grid. However, this might also mean that there is less water stored at peak load hours, restricting production potential in those times. The last set of scenarios investigates the effects on the system of those trade-offs. This part of the research is not meant to optimize operation strategy for the individual plant, but can rather be interpreted as a sensitivity analysis of the system to different implementation strategies of the PHS plants.

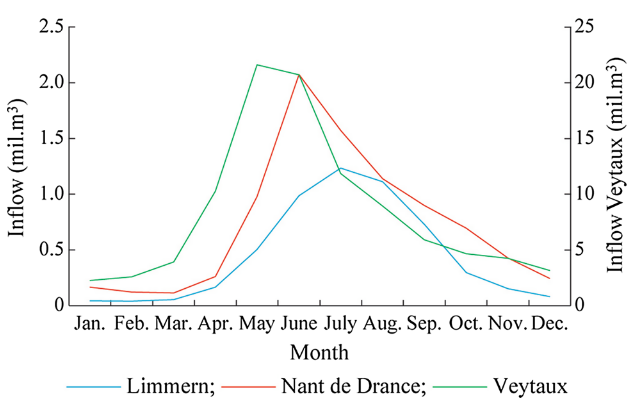


Fig. 2 Inflow into the three PHS plants, given in million m^3 of water flowing into the upper reservoirs of the PHS plants per month. Inflow into the upper reservoir of the PHS plant of Veytaux is plotted on the secondary axis for reading clarity

The three Swiss plants are added to the German electricity system. For each of the IRES-scenarios, this is done in two ways; the first scenario adds all thee PHS-plants as extra peak-load power (referred to as the PPP-scenario), and the second investigated the effect of adding the smaller Limmern and Nant de Drance as peak load, but Veytaux as middle load plant (PPM), since this plant has a very large upper reservoir.

3 Results

Table 4 summarizes the effect of adding the three Swiss PHS plants (the SwB scenarios in Table 4) to the German electricity system. First, results are given on the scenarios of the German system *without* the Swiss PHS plants, followed by the two sensitivity-tests performed on the system: investigating merit-order effects (PPP versus PPM) and taking local hydrology into account (no inflow versus inflow).

In Table 4, scenario names refer to the different systems modeled: first, data is given for the electricity system of Germany in 2050 containing high shares of IRES (sub-scenarios *solar*, *mix* and *wind*). Total electricity production in 2050 equals 594 TWh for all scenarios. Swiss plants are added to the system in four different ways: differently installed in the merit-order (all in peak load - PPP versus two in peak and one in middle load - PPM) and with or

Table 4 System stability indicators for the German electricity system

			LOLP (Days/yr)	Shortages (GWh)	Surpluses (TWh)
Germany		*solar*	7.0	931.9	17.1
		mix	7.0	881.3	5.4
		wind	7.0	807.6	2.3
SwB-PPP	no inflow	*solar*	5.6	668.4	16.8
		mix	5.3	618.9	5.1
		wind	4.1	484.2	1.9
	inflow	*solar*	5.3	639.2	17.0
		mix	5.3	614.7	5.2
		wind	4.1	480.3	2.0
SwB-PPM	no inflow	*solar*	5.9	764.9	16.3
		mix	6.0	712.6	4.9
		wind	5.0	567.6	1.8
	inflow	*solar*	5.4	674.0	16.9
		mix	6.0	706.6	4.9
		wind	4.9	561.9	1.8

without taking hydrology into account (no inflow versus inflow).

The LOLP's of the three sub-scenarios *solar*, *mix* and *wind* of the German electricity system (see Table 4) all equal 7 days per year, since the stability of the system is used to develop comparable scenarios. More shortages arise in the *solar*-dominated system (931.9 GWh), although this is not translated into a different LOLP (recall the description of LOLP versus shortages of Section 2.1). Furthermore, Table 4 shows that the *solar*-scenario has 7.5 times more surpluses compared to the *wind*-scenario; 17.1 TWh of energy is thus not used annually, which relates to the different capacity factors and the difference in patterns of the used technologies.

In general, the system becomes more stable when the three Swiss PHS plants are added to the German electricity system (see Table 4). This holds for each of the three IRES scenarios, and for both the PPP and the PPM scenario. In other words, the LOLP drops in all cases, as well as the amount of shortages and surpluses. The drop in shortages and surpluses illustrate the battery function of the three plants; surpluses are "absorbed" by the PHS-plants, which in turn allows for a production increase, i.e. lowering the shortages.

3.1 Merit order effects on system performance

Comparing the results in Table 4 for the PPP-scenarios with the PPM-scenarios shows that when Veytaux serves in middle load (PPM), the amount of surpluses drops slightly, but the amount of shortages and the LOLP increases in all cases. In other words, more storage is taking place, lowering the overall surpluses within the system, but this is not translated to increased production. Note that when a PHS-plant serves more load hours (i.e. when it stands lower in merit order), this automatically leads to lowered upper reservoir levels, which in turn allows for a storage increase. However, serving more load hours also implicates less water stored at peak times. This explains why the electricity systems with Veytaux implemented in middle load (i.e., the PPM-scenarios) have a higher LOLP compared to the ones with all PHS-plants serving in peak-load. Those results illustrate that it matters where the plants are functioning in the merit order.

An additional explanation for the lower system stability of the PPM-scenarios can be found in the *interaction* of the PHS-units within the electricity system. As the large upper reservoir of Veytaux absorbs more surpluses when it serves in middle load, fewer surpluses remain in the system that can be used to fill up the smaller reservoirs. Consequently, having less water in their upper reservoirs, those smaller PHS-plants are less capable of producing during peak times. In other words, their installed capacity is constrained by water availability.

Table 5 Full Load Hours for the three Swiss PHS-plants given for the inflow scenarios

PHS-plants	PPP			PPM		
	solar	*mix*	*wind*	*solar*	*mix*	*wind*
Limmern	198	200	227	186	197	225
Nant de Drance	170	164	187	160	161	185
Veytaux	233	236	229	4611	1697	1444
Totals	601	600	643	4957	2055	1854

The increased production of the Veytaux PHS-plant in the PPM-scenario holds for all three IRES-scenarios, but is strongest in the *solar*-scenario. Table 5 gives the amount of Full Load Hours for the three different PHS-plants when those are added to the German system. Both merit-order approaches are given (PPP and PPM), from the scenarios that took inflow into account.

In the *solar*-scenario, the Load Hours for Veytaux increase from 233 hours to 4611 hours on an annual basis; meaning that the plant is active during more than 53% of the year when it serves in middle load. The difference between the PPP and PPM scenario for the *wind*-system implies an increase from 229 to only 1444 load hours for Veytaux. This clearly illustrates the need for a diurnal counterbalance when a lot of photovoltaics are installed. Within the PPP scenario, the three Swiss PHS-plants serve more full load hours in the *wind*-scenario, but the relative contribution of the different plants differs per IRES scenario.

3.2 Inflow into the reservoirs

When inflow is taken into account, the LOLP drops for all scenarios (see Table 4). This means that the Swiss inflows add stability to the German electricity system. This is also reflected in the number of shortages; less shortages remain in the inflow-scenarios. In other words, the PSH plants generate some of the delivered power by the use of inflowing water.

Considering that the shortage drop from no inflow to inflow is stronger in the *solar*-scenario than in the other two IRES scenarios, this implicates that a *solar*-dominated electricity system profits more from taking local hydrology into account. The explanation of this lies in the timing of the original shortages, which manifest more often during winter (see Section 3.4).

Because the water flows into the upper reservoirs, there is less space to store the surpluses that arise on the German side of the system, which increases the number of surpluses in the inflow-scenarios. This indicates a potential conflict of electricity storage versus the storage of natural inflow. When all plants serve in peak load, this leads to an increase of 0.1–0.2 TWh of surpluses that remain within the German system on an annual basis. However, when the large upper reservoir of Veytaux serves in middle load (PPM-scenarios), the number of surpluses that remain un-stored increase stronger in the *solar*-scenario compared to the other IRES-scenarios (0.6 TWh versus 0). Thus, the conflict between pumping and natural inflow happens most often in the PPM+*solar*-scenario. This is the result of the increased pumping potential (allowed by lower water levels as explained in Section 3.1) combined with the clustering of both the surplus- as well as the inflow peak during the summer months.

3.3 Comparison of the IRES scenarios

In all four different ways of implementing the Swiss PHS-plants to the German electricity system, the *wind*-scenario is the most stable of the three IRES-scenarios (Table 4). Thus, a system with high shares of wind implemented in the electricity network can profit more from the addition of PHS to the electricity mix compared to systems with a larger role for solar-PV.

In Fig. 3, each spike represents one loss of load event. The magnitude of the spike gives the power difference between supply and demand within the specific hour. In orange and blue (resp solar and wind) the hourly shortages are given when only the German electricity system is modeled, in red and green (resp solar and wind) the shortages that remain after the three Swiss PHS-plants are added. Fig. 3a gives results for the solar-scenario in week 3 and Fig. 3b in week 39. Fig. 3c gives results for the wind-scenario in week 3 and Fig. 3d for the wind-scenario in week 39.

This can be explained by looking at the magnitude of the shortages in the original German system. Those are plotted in Fig. 3 together with the shortages within the SwB-PPP scenario. In order to be able to explain the underlying mechanism, two exemplary weeks are shown and shortage data is given per hour.

Figure 3 shows that in the *solar*-scenario (Fig. 3a and Fig. 3b), the magnitude of the separate shortage event drop when the three Swiss PHS-plants are added, but the number of shortage events does not change. In both weeks, four LOLP-hours can be counted both for the German-scenario as well as in the SwB-scenario. The *wind*-scenario (Fig. 3c and Fig. 3d) gives rise to a different picture in the same weeks. When only the German system is modeled, there are six shortage events in week 3 (Fig. 3c, blue). When the Swiss plants are added (SwB PPP), this drops to three peaks (Fig. 3c, green). During the third week of September, there were initially five shortage events (Fig. 3d, blue), of which none remains when the Swiss PHS-plants are added (Fig. 3d, green). Thus, more loss-of-load-events, with larger magnitudes, remain in the *solar*-scenario compared to the wind scenario, although the events are lower in magnitude after the Swiss plants are added to the system.

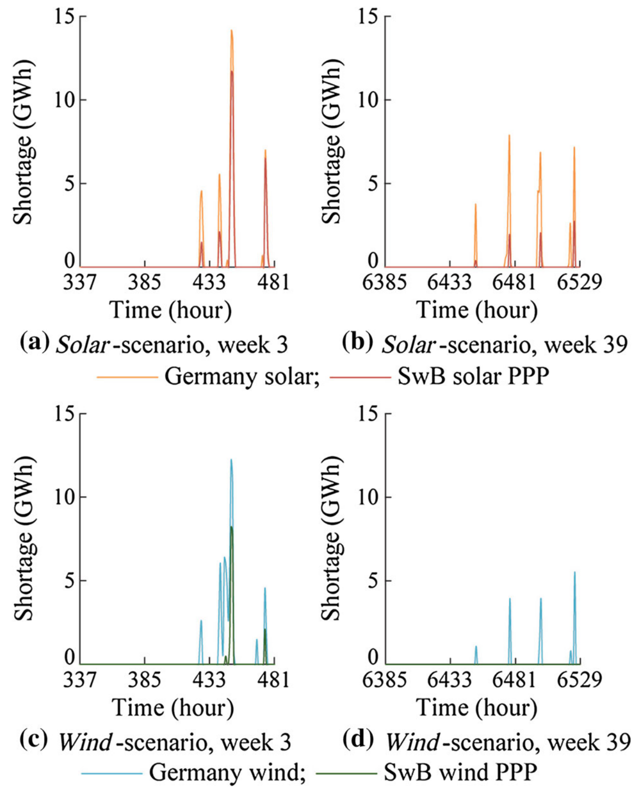
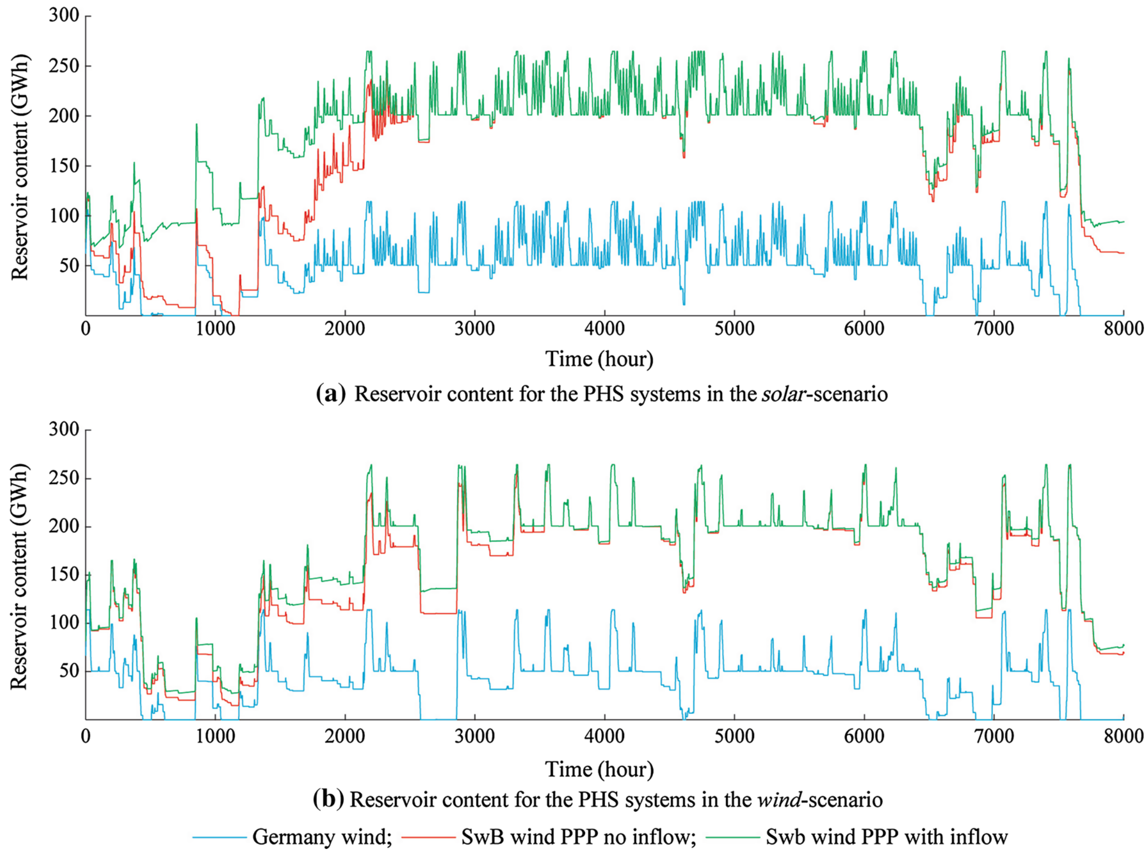


Fig. 3 Shortages (in GWh) per hour for two exemplary weeks (3rd week of January and 3rd week of September). Each spike represents one loss of load event. The magnitude of the spike gives the power difference between supply and demand within the specific hour. In orange and blue (resp solar and wind) the hourly shortages are given when only the German electricity system is modeled, in red and green (resp solar and wind) the shortages that remain after the three Swiss PHS-plants are added. (**a**) Gives results for the solar-scenario in week 3 and (**b**) in week 39. (**c**) Gives results for the wind-scenario in week 3 and (**d**) for the wind-scenario in week 39

3.4 Pattern analysis

Figure 4 gives the reservoir content on an hourly basis of the complete PHS-park. Both the *solar*- and the *wind*-scenarios are depicted, with the results for Germany only, and both the SwB-PPP no inflow and inflow scenario. Results are plotted for the PPP-scenarios only and also the *mix*-scenario is left out of this analysis since its behavior lies between those two extremes.

Note that the German system contains some installed PHS-capacity itself (see Table 2), meaning that a full reservoir for the German-only scenario peaks at 114.2



(a) Reservoir content for the PHS systems in the *solar*-scenario

(b) Reservoir content for the PHS systems in the *wind*-scenario

Fig. 4 Reservoir content on an hourly basis of the *solar*-(**a**) and the *wind*-(**b**) scenarios for Germany only (in *blue*), and both the SwB-PPP no inflow (*red*) and inflow (*green*) scenario. Note that the German system also contains some installed PHS-capacity itself (see Table 2), meaning that a full reservoir for the German-only scenario peaks at 114.2 GWh. The addition of the three Swiss plants adds 150.6 GWh, summing to a total of 264.8 GWh installed storage capacity

GWh. The addition of the three Swiss plants adds 150.6 GWh, summing to a total of 264.8 GWh installed storage capacity. Under all scenarios the reservoirs reach the maximum installed storage capacity (114.2 GWh or 264.8 GWh) during summer, which indicates that the potential to absorb summer surpluses is limited by storage capacities of the upper reservoirs.

When comparing the usage of the PHS-plants within the German system (blue lines), the graphs show that a higher frequency of use can be observed in the *solar*-scenario compared to the *wind*-scenario, especially during the summer months. Figure 4 shows that the storage capacity delivered by the German PHS-sector is less often needed when more wind is implemented in the network, which relates back to the capacity factors as given in Section 2.2.1.

The natural inflow into the systems can be observed during the first months of the year (from ~800 hours till 2500 hours). Lowering demands and an increase in IRES-production cause a reservoir filling in the no inflow- scenarios (given in red), but this process starts earlier in the year when inflow is taken into account (green lines). In other words, reservoir levels are higher earlier in the year. This is especially the case in the *solar*-scenario (upper graph) around February (i.e., from hour 744 to 1416). When no inflow is taken into account, reservoirs reach very low levels in this month, indicating that production is constrained by water availability, resulting in higher LOLP values drop (Table 4).

Figure 4 shows furthermore that increasing winter demand causes the lake levels to drop during autumn. Note however that the sum of reservoirs is never empty in both the solar- and wind-scenario when inflow is taken into account (green line in Fig. 4a and Fig. 4b). The increase of storage in the last week of December is caused by a low demand (Christmas holiday) and a high production from wind. As was shown in Table 4, some shortages remain in all IRES-scenarios. In all scenarios, shortages manifest during winter, at times where upper reservoirs are emptied. Since shortages remain also in the Swiss inflow-scenarios, where upper reservoirs are actually never emptied fully, this indicates a maximum usage of the turbines within those specific hours.

4 Conclusion

This research aimed to assess the potential of Switzerland to stabilize Germany's future electricity system, while taking into account the intermittency of Renewable Energy Sources as well as the temporal variation of the hydrology surrounding a PHS plant. The PowerPlan model was used to simulate the German electricity system in 2050, assuming 80% renewables. This led to three scenarios of the German system (*solar*, *mix* and *wind*). The potential role of the Swiss battery was tested by adding three new PHS plants to the German systems in two ways: merit-order effects were investigated and the effects of taking local hydrology into account.

Results show that the Swiss PHS-plants can play an important role in stabilizing the German grid. In the *solar*- and *mix*-scenario the results show that shortages remain, especially towards the end of winter. But when more wind is integrated in the German grid, shortages (in GWh) and number of shortages (LOLP) drop considerably. Still, even in the *wind*-scenario shortages remain due to maximum usage of installed storage capacities (in summer) or empty upper reservoirs (in winter). Results show that the PHS-plants are most useful in a *wind*-dominated scenario since these scenarios show the largest decrease in LOLP as well as in shortages and surpluses. This can be explained by the smaller amount of shortage so that the extra PHS capacity is enough to fully fulfil the demand in those hours.

Since surpluses manifest mainly during summer while demands peak during winter, a seasonal storage solution would have been interesting. This research shows however that this is not entirely possible.

In all scenarios, some shortages remain during winter and reservoir sizes restrict storage increase over summer. On the contrary, unused capacity is left to be used by other countries than Germany during summer months, especially in the *wind*-scenario and when PHS-plants are used as peak load units.

Patterns analysis of the hourly calculations showed that in the solar-scenario, the PHS-plants are mainly used to solve the daily fluctuations while in the *wind*-scenario this is not the case. This is caused by the diurnal pattern of photovoltaics.

In terms of system stability, the "battery system" functioned only slightly differently when local hydrology was taken into account. Some extra production was gained from water inflow during the winter and early spring months. The *solar*-scenario profits most from adding inflow since the IRES surpluses are lowest in these months for this scenario. Given that this scenario required in itself the largest overall installed capacity (Table 2), and is the one that responds strongest to extra production potential, these findings illustrate the limits of usefulness of large amounts of photovoltaics in the German electricity system.

Furthermore, this work suggests a potential conflict between the electrical storage function of the new plants and the storage of natural inflow, since the surpluses in the system remain higher when local inflow is taken into account. This is important, since large shares of IRES within an electricity system do not only lead to a lower reliability of supply, but also give rise to major concerns on the number of surpluses on the grid.

The Merit-order sub-scenarios (PPP and PPM) show that the merit order of the implemented PHS-plants has an influence on the behavior of the system: more surplus absorption is possible in middle load, but this leads in turn to a higher LOLP in this situation. Operators will always seek for optimal strategies in balancing the options to pump-up surpluses and generate in time of shortages. The three Swiss PHS-plants amplify this balancing problem because two PHS-plants with the smallest storage capacity have the largest generating capacity which makes them mainly capable for short time storage and production; the results showed that the placement within the merit-order of one PSH plant could constrain the functioning of the other. Furthermore, the result that more surpluses arise in the PPM-solar scenario, indicates the importance of carefully looking at the time-aspects of surpluses and inflow (in this case both during summer) in relation to the merit order. This precise planning is out the scope and possibilities of this research but this is recommended for future research.

Comparison of the IRES-scenarios showed that in order to create an equally stable system, less installed capacity was necessary for the *wind*- versus the *solar*-scenario. This result is based upon the demand pattern of Germany and may be different in countries where electricity demand patterns show different seasonality.

As concluded in the beginning of this section, the Pumped Hydro Storage plants can play an important role in stabilizing electricity system with a high penetration of IRES. When comparing equally stable systems, but with different set of IRES implemented, it was shown that the addition of a battery was more beneficial for an electricity system with a larger role for wind power. Natural inflow was found to stabilize the systems slightly, especially in the *solar*-scenario. Furthermore, the observed conflict with electricity storage and the storage of natural inflow gave rise to higher surpluses remaining in the electricity system of Germany.

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Appendix A

See Table A1.

Table A1 Plant characteristics

Type	De-rated (O&M) fraction	Must run (percentage)	Efficiency*
Nuclear	0.11	100	
Solar	0.05	100	
Wind Onshore	0.05	100	
Wind Offshore	0.05	100	
MSW	0.24	100	0.19
R-Hydro	0.1	100	
S-Hydro	0.1	0	
Coal	0.2	0.5	0.39
Biomass	0.2	0.5	0.35
Pump-Hydro	0.18	0	
CC	0.18	0	0.55
Gas turbine	0.1	0	0.29

Note: * Combustion plants only

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